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MEASUREMENT OF CABIN AIR QUALITY ABOARD COMMERCIAL AIRLINERS

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Abstract—Between April and June 1989, 92 randomly selected flights were monitored to determine prevailing levels of environmental tobacco smoke (ETS) and other pollutants in the airliner cabin environment. The monitored flights included 69 smoking flights, 8 of which were international, and 23 nonsmoking flights, all of which were domestic. Selected ETS contaminants (nicotine, respirable suspended particles and carbon monoxide), as well as ozone, microbial aerosols, carbon dioxide and other environmental variables were measured in different parts of airliner cabins. Particle and nicotine concentrations were highest in the smoking section and were somewhat higher in the boundary region near smoking than in other no-smoking sections or on nonsmoking flights. Levels of these ETS tracers were correlated with smoking rates observed by field technicians, and their levels in the boundary section were higher when more proximate to the smoking section. CO_2 levels were sufficiently high and humidity levels were sufficiently low to pose potential comfort problems for aircraft occupants. Ozone levels were well within existing standards for airliner environments, and levels of microbial aerosols were below those in residential environments that have been characterized through cross-sectional studies.

Key word index: Indoor air quality, airliner cabin, monitoring, environmental tobacco smoke, carbon dioxide, ozone, microbial aerosols, air exchange, random sampling.

1. INTRODUCTION

1.1. *Background*

The airliner cabin environment has been of great concern for the last 20 years to various elements of the U.S. Federal Government, special interest groups organized to advocate public or industry positions, and the general public itself. Passenger complaints about smoking led to segregating smoking passengers in the early 1970s. Later concerns about stratospheric ozone prompted standards (0.25 $\mu l \ell^{-1}$ maximum instantaneous level and 0.1 $\mu l \ell^{-1}$ as time-weighted 3-h standard) for the ozone concentration in airliner cabins (Federal Register, 1980).

During the mid-1980s the Committee on Airliner Cabin Air Quality, assembled by the National Academy of Sciences, performed a systematic review of existing information relating to health and safety aspects of the airliner cabin environment aboard civil commercial aircraft. The committee's report (NRC, 1986) identified several potential sources of environmental quality problems on aircraft, including tobacco smoke, ozone, cosmic radiation, humidity and microbial aerosols. The committee also recommended that smoking be banned on all commercial flights to lessen irritation and discomfort of nonsmoking passengers and cabin crew members, to reduce potential health hazards from exposure to environmental tobacco smoke (ETS) and to eliminate the possibility of fires caused by cigarettes.

Public Law 100–200, enacted in 1987 and effective for 2 years beginning in April 1988, prohibited smoking by passengers on any scheduled domestic commercial flight of 2 h or shorter duration. At the same time, the U.S. Department of Transportation (DOT) received Congressional approval to conduct a study to resolve certain technical questions related to potential continuation or broadening of the prohibitions in the law.

The purpose of the study was to develop information to be used for determining health risks from exposures to ETS for nonsmoking airliner occupants, as well as risks from other pollutants of concern for all airliner occupants. This paper reports on methods used for and results of air quality measurements conducted in the study; evaluation of health risks due

No risk assessment?

to ETS, other pollutants and cosmic radiation as well as assessment of mitigation strategies are included in a DOT report (Nagda et al., 1989).

1.2. *Prior studies*

Early studies conducted in response to passenger complaints by the Federal Aviation Administration (FAA) and Public Health Service (1971) measured cabin levels of carbon monoxide (CO), hydrocarbon vapors, total suspended particulate matter and polyaromatic hydrocarbons on 20 U.S. Air Force Military Airlift Command flights and 14 domestic flights over an 18-month period. Environmental sampling revealed very low levels of each contaminant measured, well below occupational and environmental air quality standards, and these contaminants were not judged to represent a hazard to nonsmoking passengers.

More recently, Oldaker and Conrad (1987) measured vapor-phase nicotine in no-smoking and smoking sections of three types of commercial aircraft (Boeing 727-200, 737-200 and 737-300). Average nicotine concentrations ($\pm$standard deviation) were $22.4 \pm 28.4\ \mu g\ m^{-3}$ in smoking sections, $10.6 \pm 9.7\ \mu g\ m^{-3}$ in the boundary region of no-smoking sections, and $3.3 \pm 3.6\ \mu g\ m^{-3}$ in the remainder of the no-smoking sections. The investigators did not find any significant correlation between nicotine concentrations and the number of smokers; however, smoking rates were not measured.

Data on nicotine exposures, cotinine (a major metabolite of nicotine) excretion levels, and acute symptoms from a subsequent study of passive smoking on commercial airliner flights showed that a total separation of smoking and nonsmoking sections was not achieved (Mattson et al., 1989). The study was conducted with nine subjects on four flights lasting approximately 4 h each. Two of the four flights were on aircraft with 100% outside air ventilation (Boeing 727) and the other two were on aircraft with 50% recirculation (Boeing 767). The observed nicotine levels were similar to those measured in the Oldaker and Conrad study: $13.6 \pm 23.0\ \mu g\ m^{-3}$ in the boundary region of no-smoking sections and $16.5 \pm 17.1\ \mu m^{-3}$ in smoking sections. Aircraft with no recirculation had *significantly lower nicotine concentrations than those with recirculation.*

Although these studies have been useful in suggesting ranges of concentrations of ETS tracers encountered in the general airliner cabin environment, the monitored flights were not randomly slected and the number of observations was generally small, precluding any generalization of the results. Similarly, determining factors (e.g. smoking rates, ventilation systems, seating patterns) of ETS concentrations for the general airliner cabin environment were not investigated in depth.

2. METHODS

2.1. *Measurements*

Air pollutants were selected for monitoring that had known or suspected sources in the aircraft and could be

Table 1. Measurement parameters and methods

Parameter	Sample collection method	Analysis method	Reference
ETS contaminants			
Carbon monoxide	continuous monitor	solid polymer electrolyte	Nagda and Koontz (1985)
Nicotine	sodium-bisulfate treated filter	gas chromatography—nitrogen selective detector	Hammond et al. (1987)
Respirable particles (integrated)	filtration with cyclone separator	gravimetry	Hammond et al. (1987)
Respirable particles (continuous)	continuous monitor	nephelometry	Ingebrethsen et al. (1988)
Microbial aerosols			
Fungi	impaction	culture/microscopy	Burge et al. (1987)
Bacteria	impaction	culture/microscopy	Burge et al. (1987)
Pollutants			
Ozone	MBTH*-coated filter	spectrophotometry	Lambert et al. (1989)
Carbon dioxide	detector tube	length of stain	Lynch (1981)
Other parameters			
Temperature	continuous	platinum RTD	ASHRAE (1985)
Relative humidity	continuous	thin-film dielectric sensor	ASHRAE (1985)
Barometric pressure	continuous	piezoresistance	ASHRAE (1985)
Air exchange	sorbent tube (passive)	gas chromatography of perfluorocarbon tracer (PFT)	Dietz and Cote (1982)

*3-Methyl-2-benzothiazolinone.

monitored or sampled in airliner cabins with small, unobtrusive instrumentation. The ETS contaminants monitored during the study were nicotine, respirable suspended particles (RSP) and CO. The other pollutants that were monitored were ozone and microbial aerosols. In addition, carbon dioxide (CO_2) was monitored. The monitoring package configured for the study consisted of instruments and sensors for measurement of time-varying concentrations of contaminants in addition to samplers for collection of time-integrated samples. It also included a data acquisition system for recording outputs from the continuous monitors. The instrument was packaged in a single, compact carry-on bag (46 x 23 x 23 cm high) typical of that carried by airline passengers.

Nicotine was measured through collection of time-integrated samples and CO was measured with portable continuous monitors; RSP was measured both by integrated and continuous methods, with an optical sensor in the latter case (Table 1). CO_2 and ozone were measured with time-integrated samples whereas short-term samples were collected for microbial aerosols (bacteria and fungi) near the end of each flight, prior to descent. Temperature, relative humidity and cabin air pressure were monitored continuously with portable sensors. Air exchange rates were measured using constant release and integrated sampling of perfluorocarbon tracers (PFTs). Smoking rates were estimated through technician observations of the number of lighted cigarettes during a 1-min interval every 15 min and collection of cigarette butts at the end of most monitored flights. All aspects of the measurement protocol were pretested on four commercial flights that were monitored over a 3-day period in March 1989.

Monitoring was to be performed by each technician at an assigned seat. Based on pretest monitoring at a variety of locations, the following four locations were chosen for monitoring on smoking flights: coach smoking section, boundary region of the no-smoking section within three nonsmoking rows near the coach smoking section, middle of the no-smoking section and remote no-smoking section (i.e. as far as possible from coach smoking, usually near the first-class smoking and no-smoking sections). Because less substantial variations were expected on nonsmoking flights, two locations (middle and rear of the plane) were chosen for those flights. ETS contaminants were monitored at all seat locations and other pollutants were monitored at half of the locations. The instrument package was typically placed on the technician's lap or lap tray to obtain measurements of contaminants most representative of passenger breathing levels.

Quality control procedures for integrated samples, including nicotine, RSP and ozone, consisted of daily measurements of sampler-pump flow rates in the field and submission of field blanks and duplicate samples to the analytical laboratory. Duplicates were also deployed for the passive detector tubes used to measure CO_2 levels, but the tubes were not calibrated. The optical sensors for RSP were fitted with a 10-mm cyclone to remove particles larger than 3.5 μm diameter. Prior to use in the field, these sensors were calibrated dynamically, based on exposure to ETS-RSP in an environmental chamber (Leaderer *et al.*, 1984) and an office setting, through reference to concurrent measurements with a piezoelectric microbalance and with gravimetric methods. A series of three exposures was performed in the test chamber, with relatively constant ETS-RSP concentrations generated during each test by human smokers at low, moderate and high smoking rates. In a closed office room, ETS-RSP was generated intermittently to obtain time-varying RSP concentrations.

2.2. *Selection of flights*

The target sample size for the study was 60–120 smoking flights on jet aircraft, including some international flights. A smaller set of 20–40 nonsmoking flights was targeted to provide a baseline for comparison. The target sample size for nonsmoking flights was smaller because flight-to-flight variations in ETS contaminant levels were expected to be lower than for smoking flights.

A total of 70 airports that collectively accounted for 90% of U.S. enplanements during 1987 was used as the sampling frame for selection of flights to be monitored. Airports of departure were randomly selected for study flights to provide proportional representation of airports associated with all smoking and nonsmoking flights scheduled for departure during January 1989, based on computer data files supplied by DOT. The random selections were made separately for smoking and nonsmoking flights. The specific flights to be monitored were chosen by randomly chaining together the selected airports of departure, subject to constraints relating to the smoking/nonsmoking status of flights.

3. RESULTS AND DISCUSSION

3.1. *Representativeness of the sample*

In total, 92 flights were monitored between April and June 1989. These included 23 nonsmoking flights and 69 smoking (61 domestic and 8 international) flights. The monitored smoking flights proved to be representative of types of aircraft (Fig. 1), based on a comparison with all scheduled flights in the computer data files. With the exception of Lockheed L1011s, which were overrepresented, the distributions of monitored and scheduled flights differed by no more than a few percentage points for each type of aircraft. The selected flights were also representative of airlines, flight durations and times of departure.

3.2. *Passengers and smoking*

The load factor, that is, the per cent seating capacity filled by passengers, for smoking flights averaged 76 on narrow-body aircraft (average passenger capacity of 138), and 64 on wide-body aircraft (capacity 288). For the nonsmoking flights (capacity 135), the average load factor was 70.

On average, there were 18 passengers in the coach smoking section (13.7% of all passengers). The average smoking rate per smoking-section passenger was 1.5 cigarettes per hour (range: 0.2–3.5 cigarettes per hour per passenger) during the period when smoking was allowed. An average of 68 cigarettes per flight was smoked by passengers in the coach smoking section on the monitored smoking flights. Comparative analyses indicated that smoking rates based on technician observations agreed very well with rates based on collected cigarette butts ($r = 0.9$).

3.3. *Air exchange, temperature, humidity and pressure*

The air exchange rate depends on the type of aircraft, the extent to which air can be recirculated and the extent of control that the cockpit crew has over outside air intake through selective use of air conditioning packs. The aircraft types with recirculation capabilities have lower nominal air exchange rates, ranging from 10 to 15 h^{-1} in most cases, than for aircraft without recirculation for which nominal rates vary

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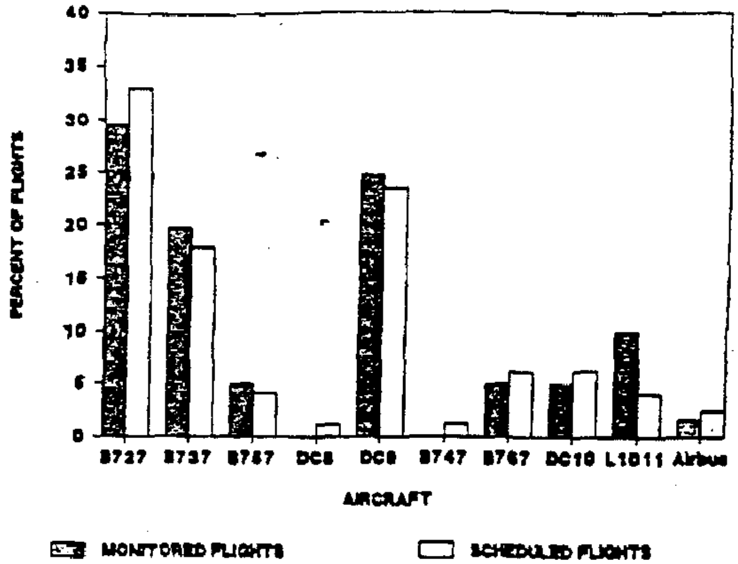

Fig. 1. Representativeness of domestic smoking flights with respect to type of aircraft.

Table 2. Nominal and measured air exchange rates by type of aircraft*

Type of aircraft	Air exchange rate (h^{-1}) Nominal	Measured†
Without recirculation		
Boeing 727-200	26.4	‡
Boeing 737-100	26.1	‡
Boeing 737-200	23.9	‡
McDonnell Douglas DC9-30	27.3	‡
McDonnell Douglas DC10-10	22.8	‡
Lockheed L1011-1/100	17.8	‡
Lockheed L1011-50	19.3	‡
With recirculation		
Boeing 737-300	14.2	17.7 ± 10.0 (9)
Boeing 747	14.7	22.4 ± 8.5 (5)
Boeing 757	15.6	27.5 ± 10.9 (4)
Boeing 767	10.4	19.5 ± 9.7 (4)
McDonnell Douglas DC9-80/ MD80	19.7	25.9 ± 9.7 (13)

* Aircraft types with only one monitored flight are excluded.
† Average ± standard deviation (number of flights).
‡ Incomplete mixing of the tracer gas resulted in errors in measurements.

from 23 to 27 h^{-1} in most cases (Table 2). These nominal values at a cruise altitude of 9.1 km are based on information provided by equipment manufacturers and airline operators (Lorengo and Porter, 1985).

For aircraft without recirculation, the measured air exchange rates were in serious error (three to five times higher than the nominal values for most flights) and thus are not shown in the table. The pattern of measurement results indicated that there generally was insufficient mixing of PFTs throughout the airliner cabin for the results to be indicative of prevailing air exchange rates. The insufficient mixing resulted from the need to remain unobtrusive during sampling, which restricted placement of PFT sources to only two locations on smoking flights and one location on nonsmoking flights. The mixing problem affected measurement results of both aircraft with and without recirculation, but particularly those without recirculation. In the case of aircraft with recirculation, there was much greater opportunity for mixing the tracer

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gas within the volume of the plane because 20–50% of the air was being recirculated. As shown in the table, the measured air exchange rates for these aircraft were generally consistent with but somewhat higher than the nominal rates.

The average measured temperature was near 24°C (range 21–27°C) for all flights. Measured relative humidity levels were quite low, ranging from 5 to 38% across all flights, but were even lower for smoking (average of 15.5%) than nonsmoking flights (average 21.5%). The average cabin pressure was lower for smoking (635 mm Hg) than for nonsmoking (686 mm Hg) flights. Both the lower humidity and the lower pressure are consistent with higher altitudes that would generally be reached on the longer-duration smoking flights.

3.4. *Environmental tobacco smoke*

Average values for various measurement parameters related to particle-phase and gas-phase ETS contaminants are summarized by monitoring location for both smoking and nonsmoking flights in Table 3. RSP concentrations were highest in the smoking section, averaging near 175 $\mu g\, m^{-3}$, and results for the gravimetric and optical methods were highly consistent. In other locations, the two methods yielded differing results. There was greater uncertainty for the gravimetric measurements due to relatively short

Table 3. Levels of ETS contaminants on smoking and nonsmoking flights

	Smoking flights				Nonsmoking flights	
Parameter	Smoking	Boundary	Middle	Remote	Rear	Middle
Particle-phase measurements						
Average RSP (gravimetric) ($\mu g\, m^{-3}$)	174.6	67.5	42.5	52.1	59.3	69.4
Average RSP (optical) ($\mu g\, m^{-3}$)	177.0	39.7	18.8	17.9	10.3	10.6
Average RSP (both methods) ($\mu g\, m^{-3}$)	175.8	53.6	30.7	35.0	34.8	40.0
Average of peak RSP (optical) ($\mu g\, m^{-3}$)	833.4	211.8	68.7	69.6	18.2	16.4
Gas-phase measurements						
Average nicotine ($\mu g\, m^{-3}$)	13.43	0.26	0.04	0.05	0.0	0.08
Per cent nicotine samples below minimum detection	4.3	54.4	82.6	66.7	100.0	78.3
Average CO ($\mu l\, \ell^{-1}$)	1.4	0.6	0.7	0.8	0.6	0.5
Peak CO ($\mu l\, \ell^{-1}$)	3.4	1.4	1.7	1.6	1.3	0.9

Table 4. Relationship between ETS measurements and smoking rates for two sections of monitored aircraft

	Smoking rate, cigs h^{-1} (number of flights)			
ETS measurement	< 10 (12)	10–19.9 (23)	20–29.9 (17)	≥ 30 (9)
Coach smoking section				
Nicotine ($\mu g\, m^{-3}$)	1.7 ± 2.4*	11.2 ± 13.0	17.6 ± 12.8	25.7 ± 21.3
Gravimetric RSP ($\mu g\, m^{-3}$)	126.2 ± 109.4	163.5 ± 88.7	191.1 ± 87.4	276.7 ± 127.2
Optical RSP ($\mu g\, m^{-3}$)	105.8 ± 47.9	150.9 ± 83.5	189.7 ± 64.0	355.1 ± 105.7
Boundary region near coach smoking				
Nicotine ($\mu g\, m^{-3}$)	0.04 ± 0.07	0.19 ± 0.07	0.17 ± 0.15	0.11 ± 0.15
Gravimetric RSP ($\mu g\, m^{-3}$)	58.8 ± 64.0	61.6 ± 47.6	79.6 ± 66.2	86.1 ± 90.5
Optical RSP ($\mu g\, m^{-3}$)	23.8 ± 17.9	24.1 ± 19.4	52.3 ± 39.2	71.8 ± 56.7

* Average concentration ± standard deviation.

Table 5. Relationship of ETS measurements in the boundary section to technician distance from smoking section

	Distance from coach smoking			
ETS measurement	One row	Two rows	Three rows	Four or more rows
Nicotine ($\mu g\, m^{-3}$)	0.11 ± 0.15*	0.34 ± 1.01	0.08 ± 0.13	0.06 ± 0.09
Gravimetric RSP ($\mu g\, m^{-3}$)	88.1 ± 64.6	64.9 ± 54.6	44.8 ± 57.1	58.9 ± 77.0
Optical RSP ($\mu g\, m^{-3}$)	50.8 ± 34.4	28.4 ± 35.8	31.5 ± 45.7	35.0 ± 30.4

* Average concentration ± standard deviation.

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monitoring durations for a number of flights. For example, 1 h of sampling duration (or about 1 h 20 min flight duration) on a nonsmoking flight would correspond to a sample volume near 0.1 m^3. For this case, a laboratory uncertainty in mass determination of $\pm 10\ \mu g$ could result in measurement values from -100 to $+100\ \mu g\ m^{-3}$ for a prevailing concentration near zero.

Cabin-wide optical results were more strongly correlated ($r = 0.6$) with smoking rates than were the gravimetric results ($r = 0.3$), and optical concentrations in the smoking section were also more strongly correlated ($r = 0.6$) with nicotine concentrations than were the gravimetric concentrations ($r = 0.5$). However, because the gravimetric method has a long history of successful use in various types of environments, neither type of measurement result can be ignored. The results obtained from averaging the results of the two methods (Table 3) indicate that differences across the no-smoking sections of the aircraft for smoking flights and differences between these no-smoking sections and nonsmoking flights were less pronounced than differences involving the smoking section. The combined results for nonsmoking flights are consistent with RSP values that have been reported for other nonsmoking environments (Repace, 1987). The 1-min peak RSP concentrations indicate some migration of ETS contaminants into the no-smoking sections on smoking flights.

Observed effects of tobacco smoking, based on gas-phase measurements, were more discernible for nicotine than for CO (Table 3). Beyond the marked increase in nicotine in the smoking section, the boundary region of the no-smoking section was most affected. Differences between nicotine levels for the remaining no-smoking locations and levels on nonsmoking flights were within the range of measurement uncertainty, but nicotine levels were more often above detection limits in the no-smoking locations of smoking flights than on nonsmoking flights. The only discernible effect for CO was in the smoking section itself. CO levels were generally highest before aircraft were airborne, both for smoking and nonsmoking flights, due to intrusion of ground-level emissions.

Both nicotine and RSP concentrations in the coach smoking section were strongly related to observed smoking rates in that section (Table 4). This relationship also persisted in the boundary region near coach smoking, though not as strongly. For the other no-smoking sections, there was no apparent relationship between ETS levels and smoking rates. Within the boundary region, ETS concentrations generally were higher when the technician was seated within one or two rows of coach smoking than when the boundary seat was three or more rows away (Table 5).

Results of statistical tests to contrast levels of ETS contaminants on smoking versus nonsmoking flights and among the different sections of smoking flights are given in Table 6. Comparisons were made using both parametric and nonparametric tests, as the nonpara-

Table 6. Results of statistical contrasts of ETS levels

	Smoking vs nonsmoking flights*				Different sections of smoking flights†			
	Parametric test (t-test)		Nonparametric test (Mann-Whitney U)		Parametric test (paired t-test)		Nonparametric test (Wilcoxon matched pairs)	
Measurement parameter	Smoking or rear	Middle section	Smoking or rear	Middle section	Smoking vs boundary	Boundary vs middle	Smoking vs boundary	Boundary vs middle
Gravimetric RSP	+	0	+	0	++	++	++	++
Optical RSP (average)	+	+	+	0	++	++	++	++
Optical RSP (peak)	+	+	+	+	++	++	++	++
Nicotine	+	0	+	0	++	++	++	++
CO (average)	+	+	+	+	++	00	++	++
CO (peak)	+	+	+	+	++	00	++	00

* + Indicates that smoking flights are significantly higher than nonsmoking flights ($p < 0.05$); 0 indicates that the difference between flights is not significant.

† ++ Indicates that the first section listed is significantly higher than the second ($p < 0.05$); 00 indicates that the difference between sections is not significant.

metric tests do not require assumptions of normality or homogeneity of variances. For the smoking/rear location, levels of all six ETS measurement parameters were significantly higher ($p < 0.05$) on smoking than nonsmoking flights. For the middle location, levels were significantly higher for continuously monitored parameters (optical RSP and CO) but not for integrated-sample parameters (gravimetric RSP and nicotine). The only discrepancy between the two types of statistical tests was for average optical RSP at the middle location, for which the parametric test was significant at the 0.05 level but the significance level for the nonparametric test was 0.09.

A comparison of different sections within smoking flights showed that levels of all six ETS measurement parameters were significantly higher ($p < 0.05$) in the smoking than the boundary location. The boundary location was significantly higher than the middle location for all ETS tracers except CO. The only discrepancy between the two types of statistical tests was for nicotine at the boundary versus middle locations, for which the nonparametric test was significant at the 0.05 level whereas the parametric test had a significance level of 0.08. Thus, these tests indicate a clear difference between ETS levels in the smoking versus boundary sections and, to a lesser extent, between the boundary and middle sections, particularly for particle-phase constituents.

3.5. *Other pollutants*

Monitored ozone levels were relatively low, averaging an order of magnitude below the FAA 3-h standard of 0.10 $\mu l\, \ell^{-1}$ and never exceeding this level. Bacteria levels were higher than fungi levels and somewhat higher in smoking than nonsmoking sections, but the measured bacteria and fungi levels in all cases were low, relative to those that have been measured in residential environments through cross-sectional studies (Tyndell *et al.*, 1987).

Relatively high CO_2 levels were measured, averaging over 1500 $\mu l\, \ell^{-1}$ across all monitored flights (Table 7). Measured CO_2 concentrations exceeded 1000 $\mu l\, \ell^{-1}$, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE, 1989) level associated with satisfaction of comfort (odor) criteria, on 87% of the monitored flights. Depending on assumed CO_2 exhalation rates, measured levels were as much as twice those predicted by a cabin air quality model. Even if the measured levels were to be lowered by half, however, CO_2 concentrations would still exceed 1000 $\mu l\, \ell^{-1}$, on 24% of the study flights.

Average CO_2 levels measured at smoking and middle seats on all smoking flights (domestic plus international) were examined in relation to type of aircraft, air recirculation, air exchange rate and load factors. The strongest association was with the load factor (Table 8): CO_2 concentrations increased with higher load factors, and were particularly high for load factors above 70%. CO_2 levels were also higher on narrow-body aircraft (average 1700 $\mu l\, \ell^{-1}$) than wide-body aircraft (average near 1200 $\mu l\, \ell^{-1}$); as noted earlier, the narrow-body aircraft that were monitored had higher load factors on the average. Relationships of CO_2 levels to nominal air recirculation and air exchange rates were less pronounced.

4. CONCLUSIONS

Levels of ETS contaminants monitored during the study were substantially higher in smoking sections of the aircraft than in nonsmoking areas, and these levels were strongly correlated with observed smoking rates. There was some evidence of ETS migration to the nosmoking boundary region near the smoking section, particularly for RSP concentrations in this region that were related to smoking rates and distance from the smoking section. Monitored CO_2 levels were sufficiently high and monitored humidity levels were sufficiently low to pose potential comfort problems for aircraft occupants. Ozone levels on all monitored flights were well within existing standards for airliner environments, and monitored levels of microbial aerosols were below those in residential environments

Table 7. Average concentrations of selected pollutants on smoking and nonsmoking flights

Parameter	Smoking flights: Smoking rows	Smoking flights: Middle rows	Nonsmoking flights
Average CO_2 ($\mu l\, \ell^{-1}$)	1562	1568	1756
Per cent CO_2 samples $\geq 1000\ \mu l\, \ell^{-1}$	87.0	88.1	87.0
Average ozone ($\mu l\, \ell^{-1}$)	0.01	0.01	0.02
Per cent ozone samples $\geq 0.1\ \mu l\, \ell^{-1}$	0.0	0.0	0.0
Average bacteria (CFU m^{-3})	162.7	131.2	131.1
Average fungi (CFU m^{-3})	5.9	5.0	9.0

† ... that smoking flights are significantly higher than nonsmo... flights ($p < 0.05$); 0 indicates that the difference between flights is not significant.

† † Indicates that the first section listed is significantly higher than the second ($p < 0.05$); 00 indicates that the difference between sections is not significant.

Table 8. Relationship of CO_2 measurement results for all smoking flights to load factor

	CO_2 average ± standard deviation ($\mu l\ \ell^{-1}$)	
Load factor (number of flights)	Smoking row	Middle row
< 50% (16)	1129.0 ± 277.8	1183.0 ± 275.6
50–69.9% (12)	1211.3 ± 229.1	1153.1 ± 603.3
70–89.9% (21)	1794.2 ± 884.3	1699.9 ± 584.5
≥ 90% (20)	1910.2 ± 583.7	1745.9 ± 212.4

that have been characterized through cross-sectional studies.

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